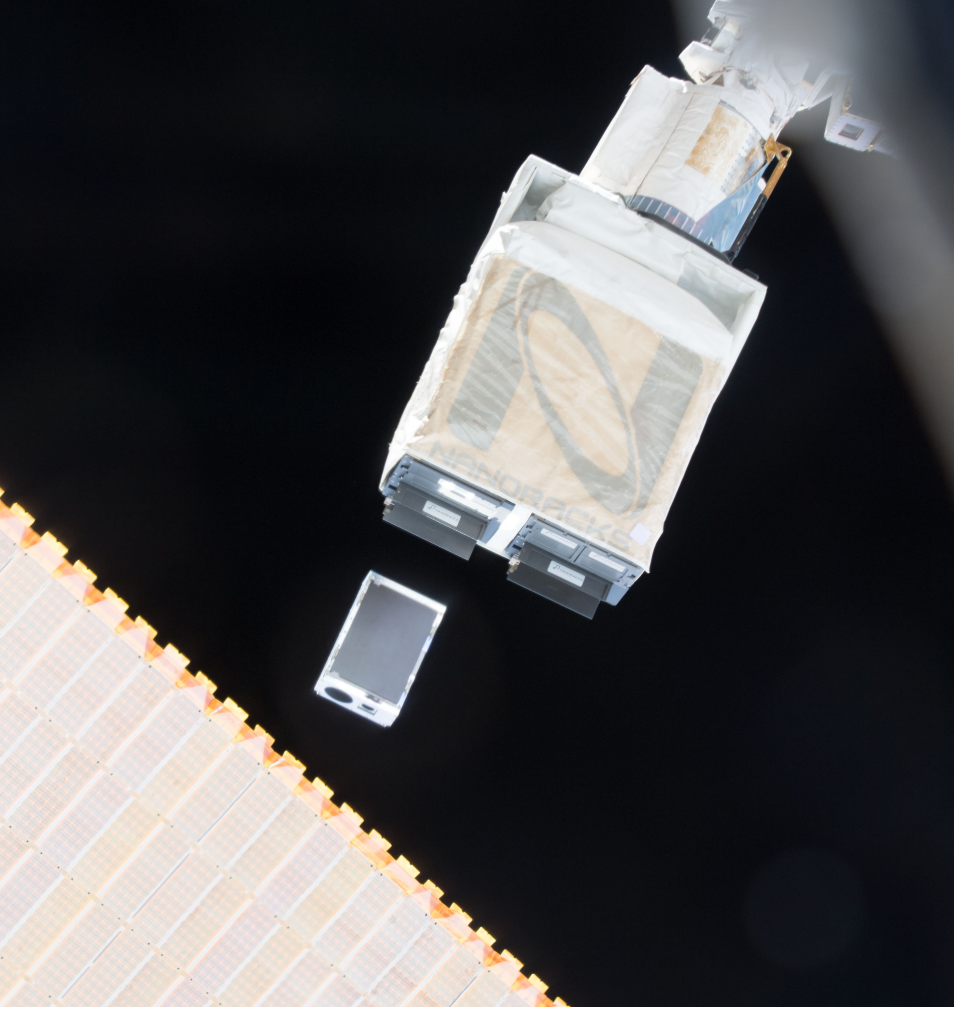

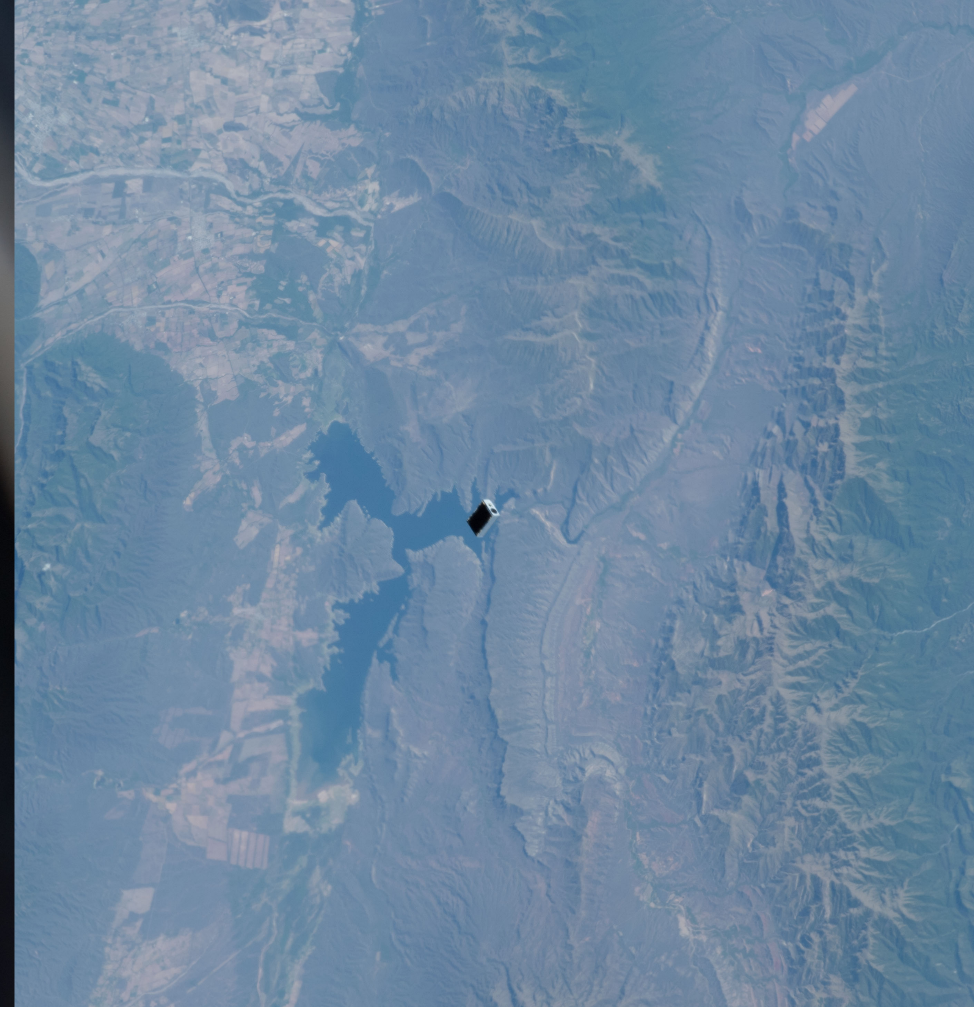

Camera Modeling, Centroiding Performance, and Geometric Camera Calibration on ASTERIA

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Jet Propulsion Laboratory
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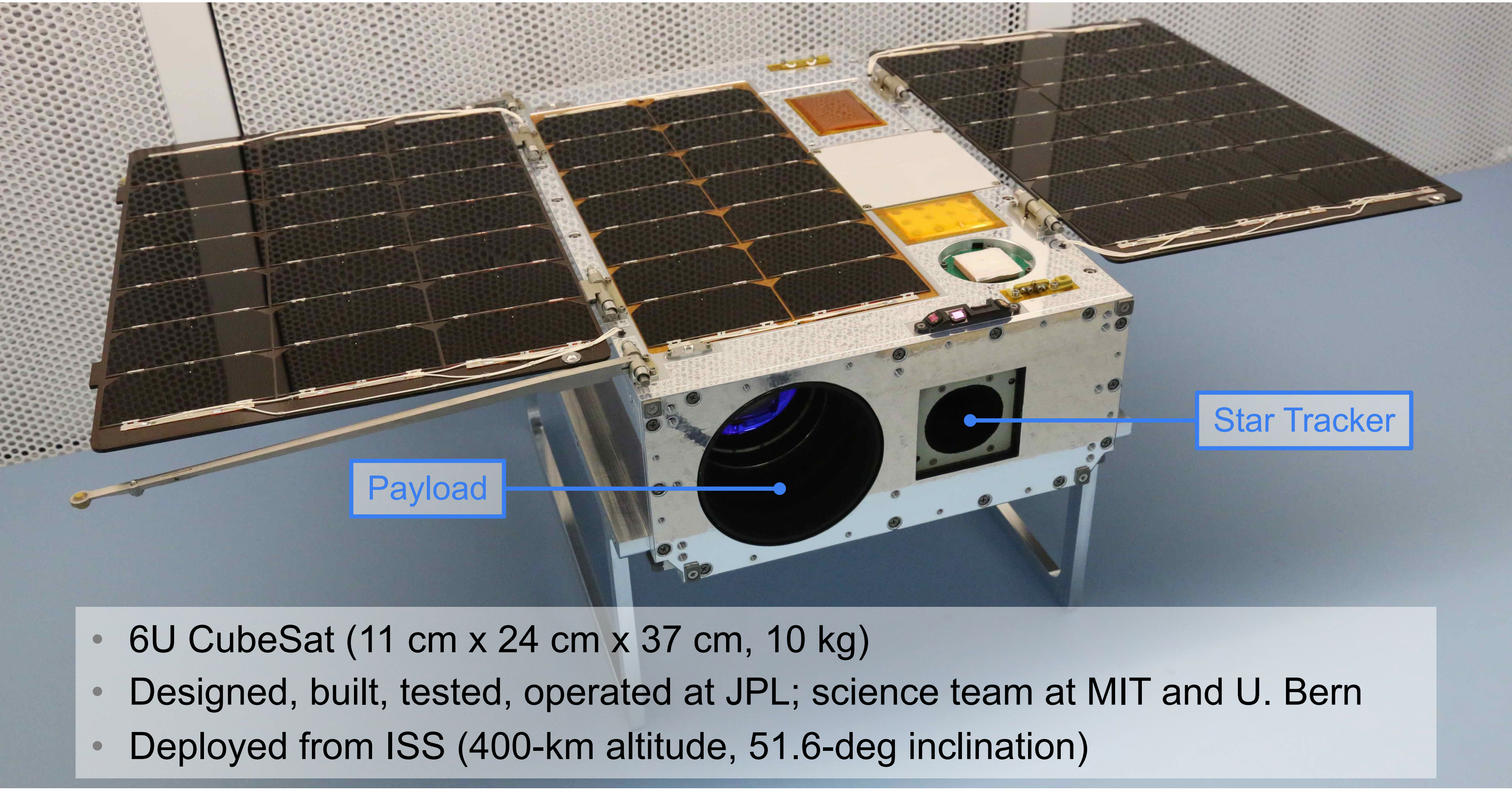
ASTERIA Overview

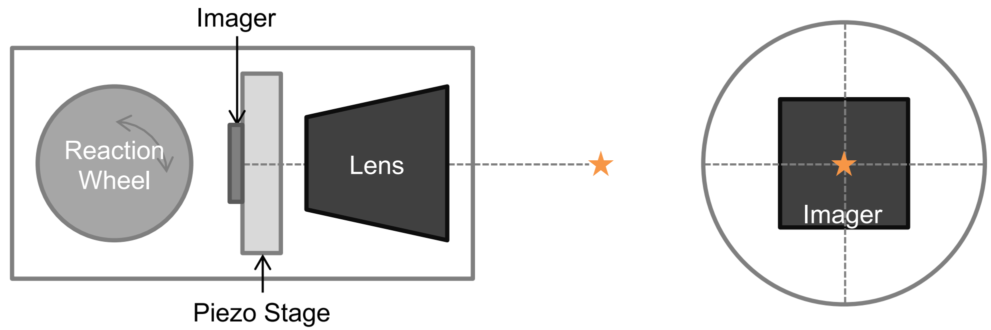


- 6U CubeSat (11 cm x 24 cm x 37 cm, 10 kg)
- Designed, built, tested, operated at JPL; science team at MIT and U. Bern
- Deployed from ISS (400-km altitude, 51.6-deg inclination)

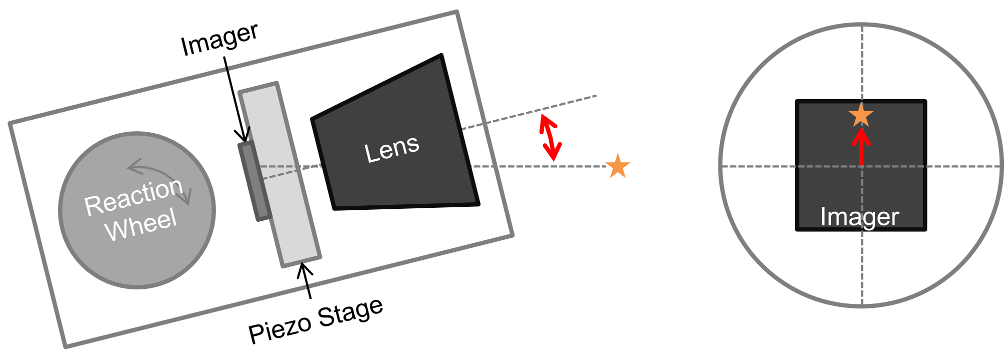
Perform photometry on bright stars, which requires repeatable and stable pointing

Two-Stage Pointing Control Concept

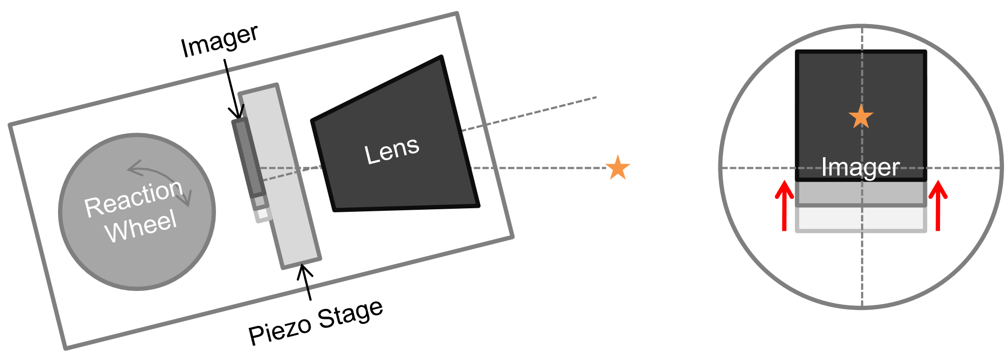
Reaction wheels point the payload to the target star



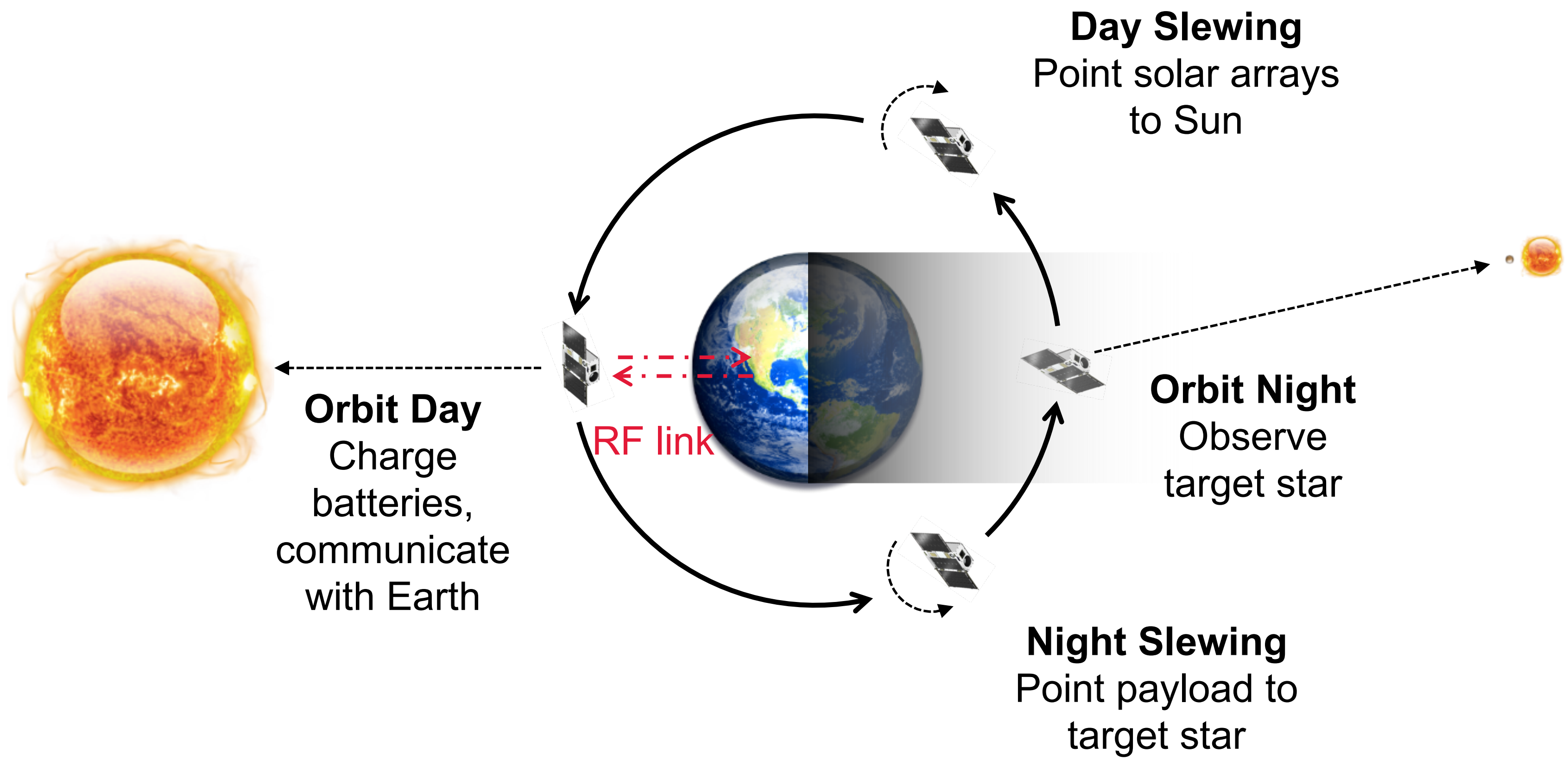
Attitude errors cause the target star to shift on the imager



Piezo stage shifts the imager to compensate for attitude errors

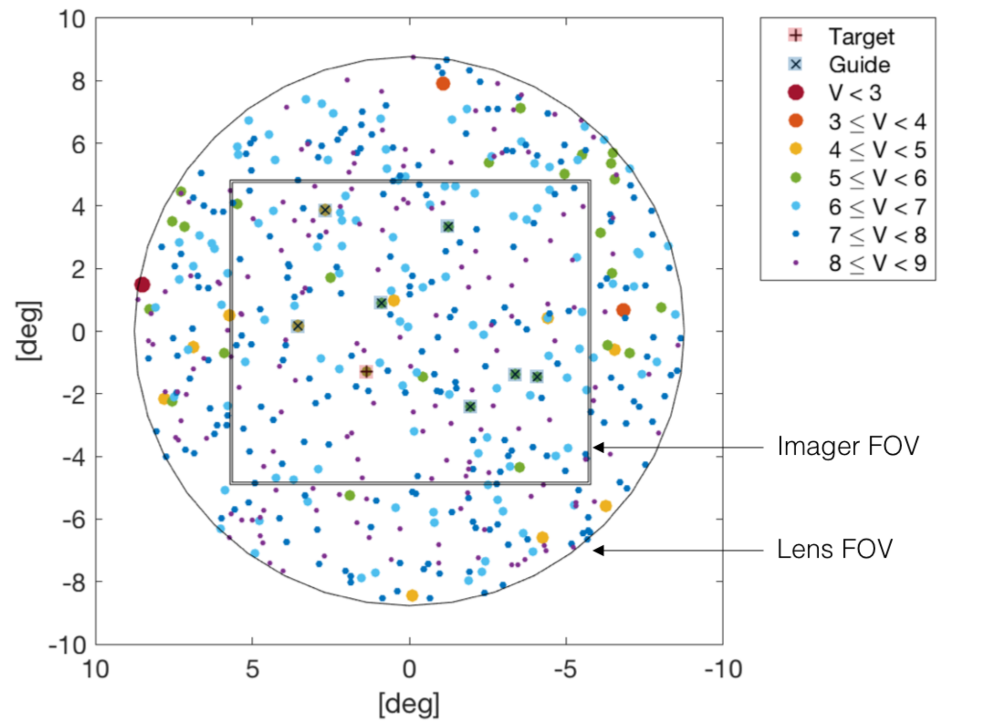


Concept of Operations for an Observation



Motivation

- Upon completing a slew to the desired star field, the imager is enabled in windowed mode, which greatly simplifies software:
  - No need to process full-frame image
  - No need to perform star identification
  - Requires a geometric camera calibration to properly predict centroid locations to place windows



- During an observation, the pointing error budget is dominated by centroid noise on the target and guide stars
  - Requires an accurate imager model to properly predict pointing performance

Geometric Camera Model & Calibration

Geometric Camera Model

1. Transform stars from J2000 to optics frame using spacecraft attitude

$$\begin{bmatrix} \boldsymbol{v}_{OP3} \\ 0 \end{bmatrix} = \boldsymbol{q}_{OP3 \leftarrow J2K} \otimes \begin{bmatrix} \boldsymbol{v}_{J2K} \\ 0 \end{bmatrix} \otimes \boldsymbol{q}^{-1}_{OP3 \leftarrow J2K}$$

2. Convert star unit vectors to centroids

Pinhole Model

$$\begin{bmatrix} x & y & z \end{bmatrix}^T = \boldsymbol{v}_{OP3}$$

$$\begin{bmatrix} u_n \\ v_n \end{bmatrix} = -\frac{1}{z} \begin{bmatrix} x \\ y \end{bmatrix}$$

Radial/Tangential Distortions

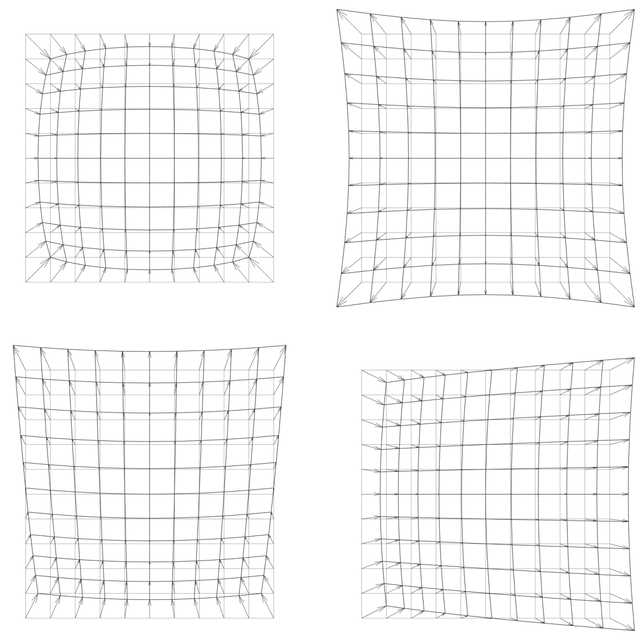
$$r_u = (k_1 r_n^2 + k_2 r_n^4 + k_3 r_n^6) u_n$$

$$r_v = (k_1 r_n^2 + k_2 r_n^4 + k_3 r_n^6) v_n$$

$$t_u = 2 p_1 u_n v_n + p_2 (r_n^2 + 2 u_n^2)$$

$$t_v = p_1 (r_n^2 + 2 v_n^2) + 2 p_2 u_n v_n$$

$$r_n^2 = u_n^2 + v_n^2$$



$$\boldsymbol{p}_{OP2}^{c \leftarrow OP2} = f \begin{bmatrix} u_n + r_u + t_u \\ v_n + r_v + t_v \end{bmatrix}$$

3. Transform star centroids to imager/window frame
4. Convert centroid to pixels

$$\boldsymbol{c}_{IMG} = \frac{\boldsymbol{p}_{IMG}^{c \leftarrow IMG}}{p}$$

Geometric Camera Calibration Procedure

- Least-squares optimization of predicted versus measured centroid errors

$$\min_{\boldsymbol{x}} \sum_{i} \left(\boldsymbol{c}_{IMG}^{p_i} - \boldsymbol{c}_{IMG}^{m_i}\right)^T \left(\boldsymbol{c}_{IMG}^{p_i} - \boldsymbol{c}_{IMG}^{m_i}\right)$$

Predicted centroids

Measured centroids

$$\boldsymbol{x} = \begin{bmatrix} \boxed{\delta\phi \quad \delta\theta \quad \delta\psi} & \boxed{k_1 \quad k_2 \quad k_3 \quad p_1 \quad p_2} & \boxed{f} \end{bmatrix}^T$$

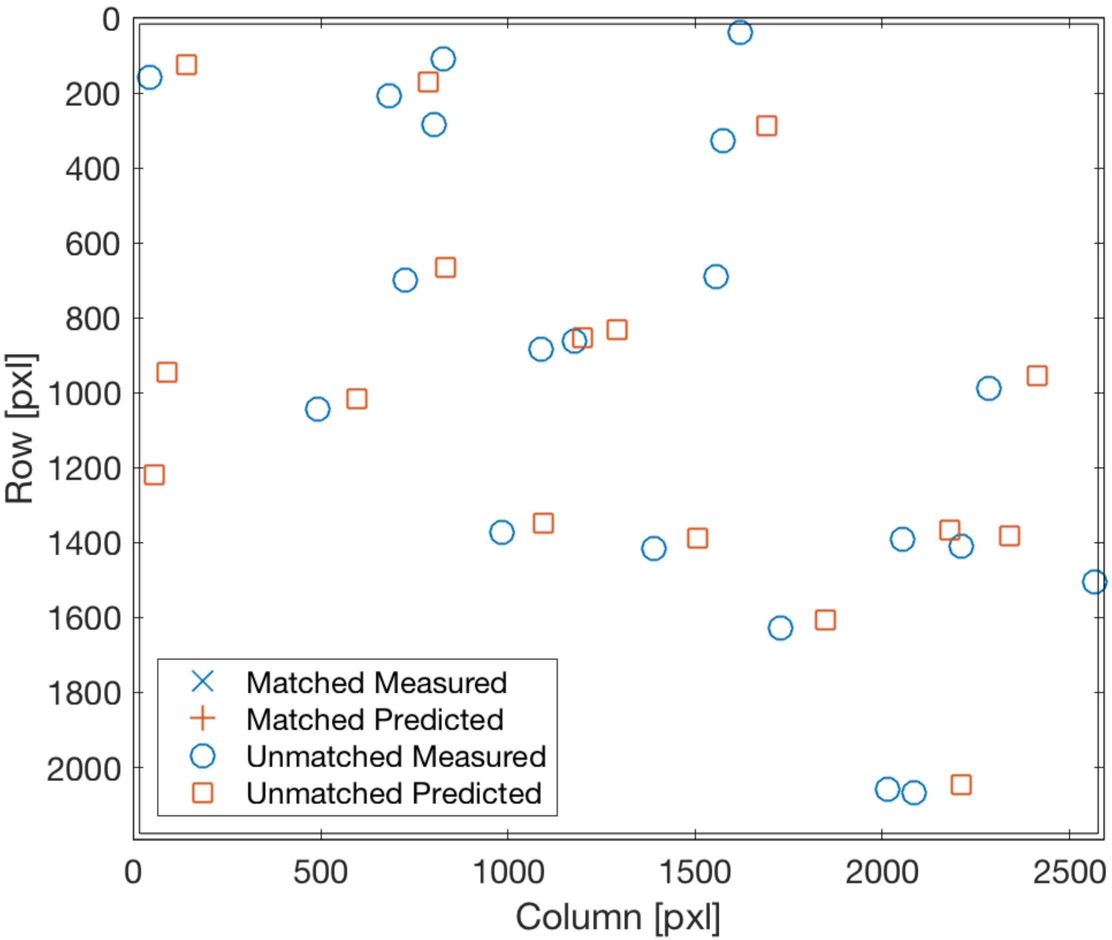
Star-tracker-to-payload alignment

Radial/tangential distortion coefficients

Focal length

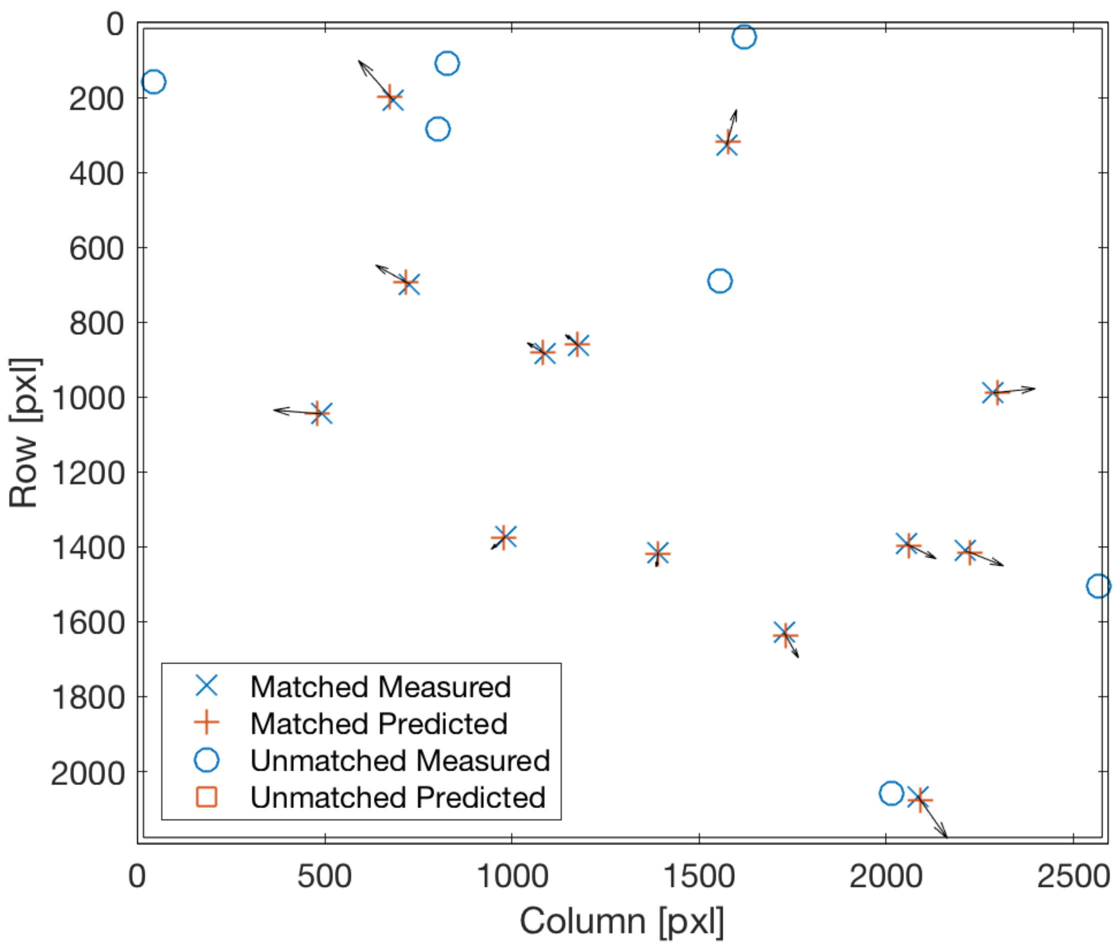
Geometric camera calibration can be performed with a single full-frame image

Measured and Predicted Centroids (Before Calibration)



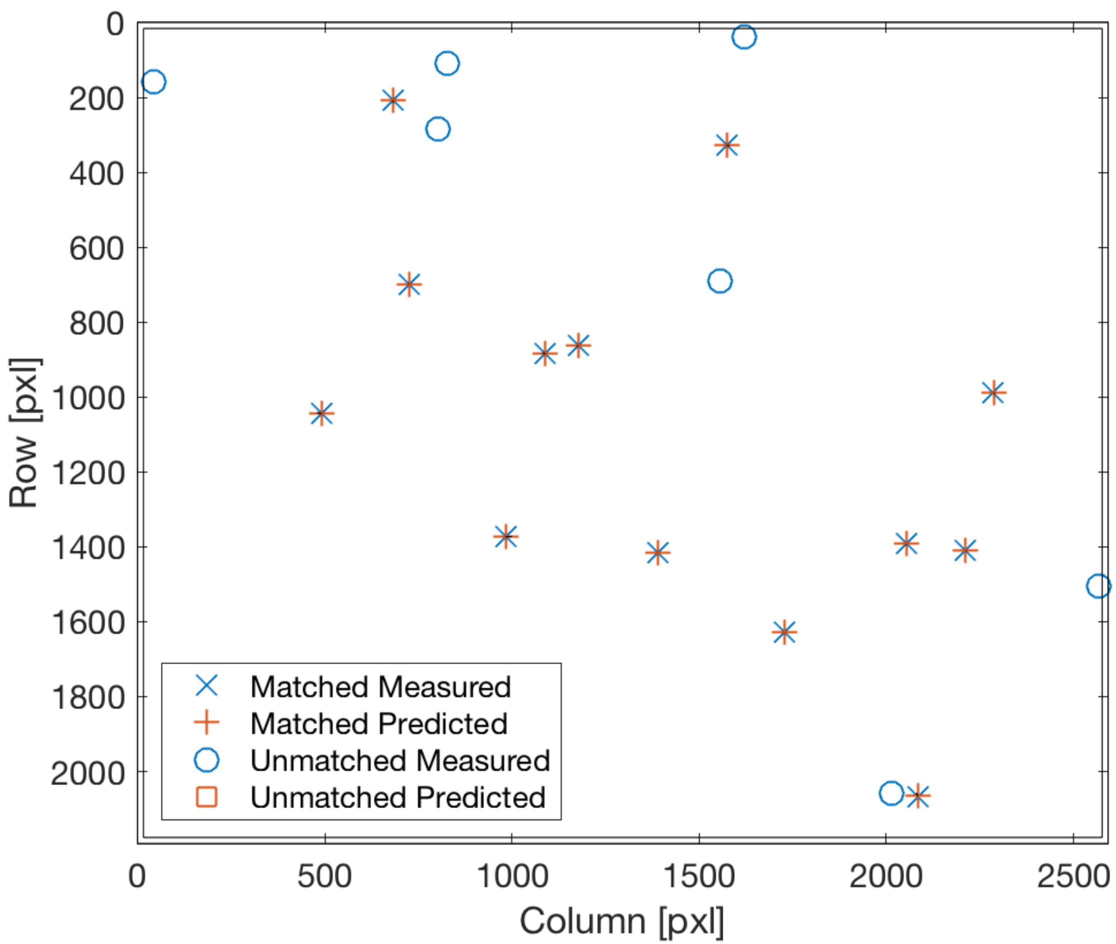
Measured and predicted centroid residuals are significant before calibration (~120 pixels)

Measured and Predicted Centroids (Alignment Calibration Only)



Star-tracker-to-payload alignment removes a significant amount of error but there is still a clear radial pattern in the residuals

Measured and Predicted Centroids (After Calibration)

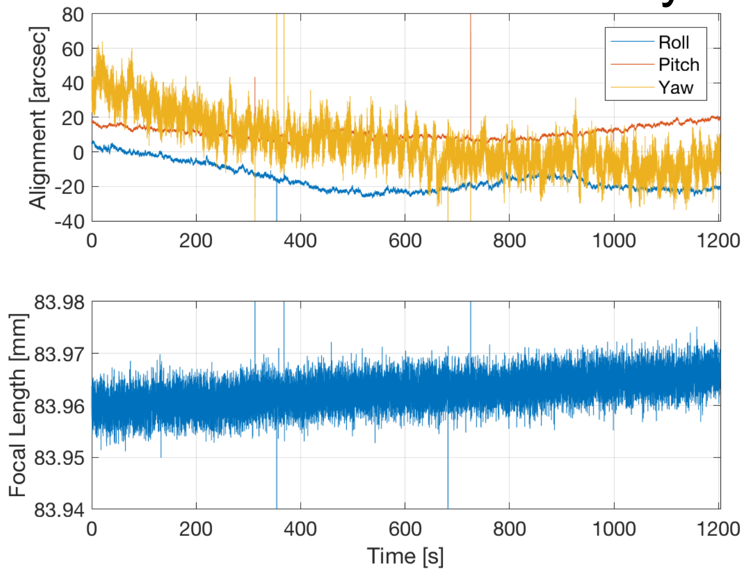


Variable	Nominal	Calibrated
$\delta\varphi$	0 deg	+0.1267 deg
$\delta\theta$	0 deg	+0.5023 deg
$\delta\psi$	0 deg	+0.1627 deg
k_1	0.4	0.4
k_2	1.7	1.7
k_3	0	0
p_1	0	0
p_2	0	0
f	85 mm	83.94 mm

Residuals are 0.5 pixels RMS after calibration, allowing window locations to be accurately predicted on the ground

Calibration Change over Time

- To see how the calibration parameters change over time, calibration procedure can be run for every RTI in an observation



- Star-tracker-to-payload alignment changes are significant (on the order of an arcminute)
- Focal length changes are insignificant (on the order of microns)

- A shaping filter (fed with unit white noise) was created to bound the star-tracker-to-payload alignment changes over many observations

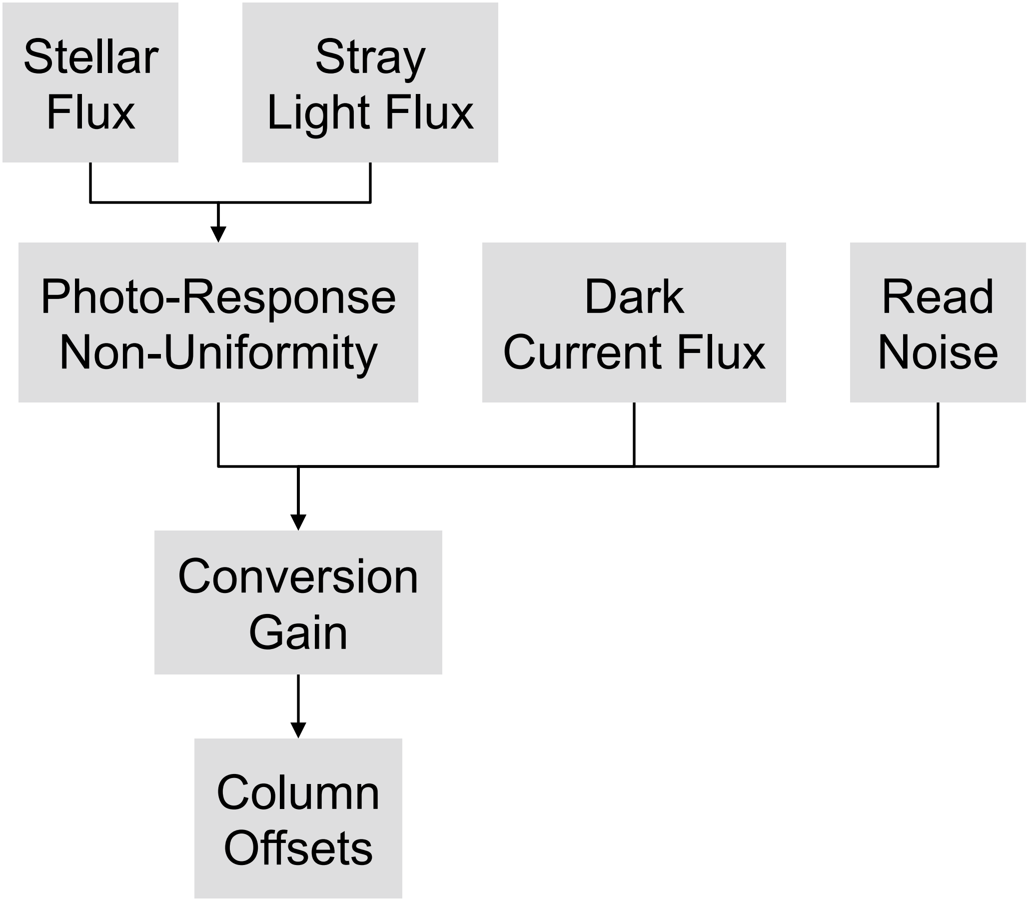
$$G(s) = a\left(\frac{b}{s+b}\right)^2$$

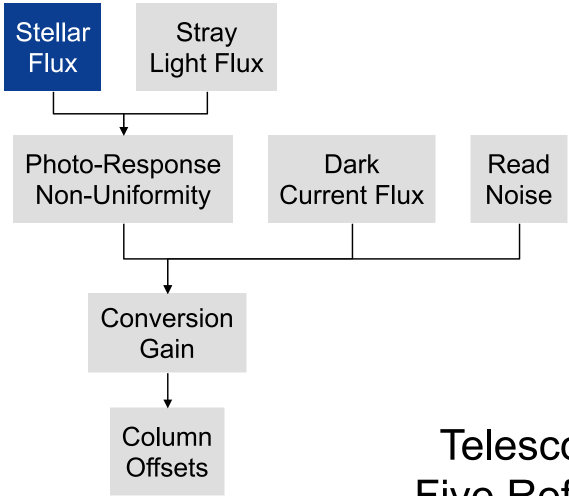
a = 0.011
b = 0.01 rad/s

A model of star-tracker-to-payload-alignment drift was created, which can be used in an error budget and serves as a useful data point for other missions

Imager Model & Centroiding Performance

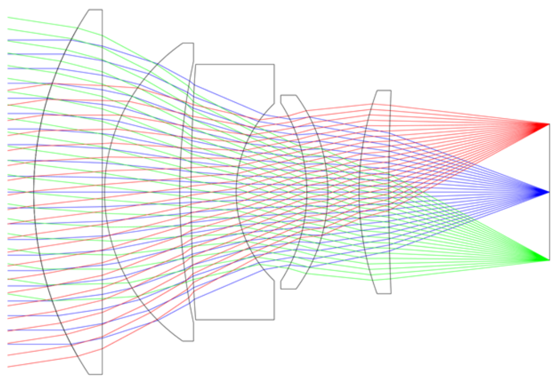
Imager Model Block Diagram



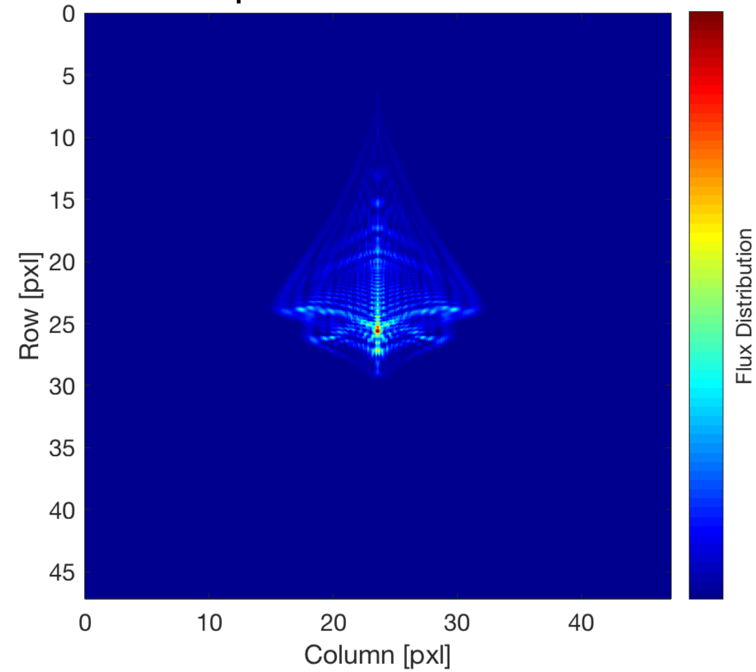


Generate Point Spread Function (PSF)

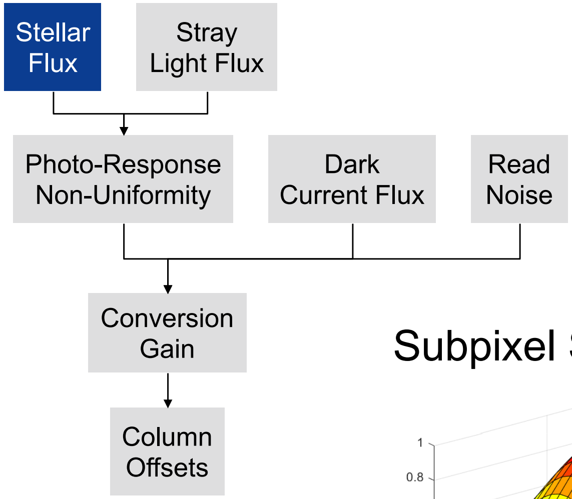
Telescope Design with Five Refractive Elements



Example of Aberrated PSF

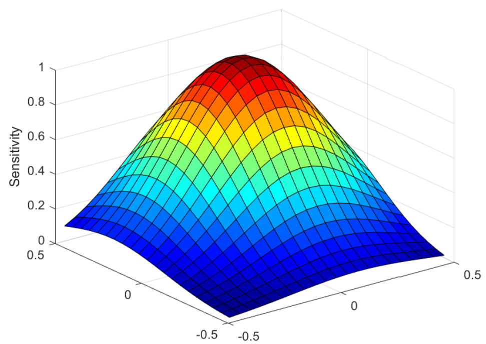


- Zemax model was used to generate point spread functions at different field points
  - Randomized decenter based on mechanical tolerances
  - Compensated with focal plane tilt

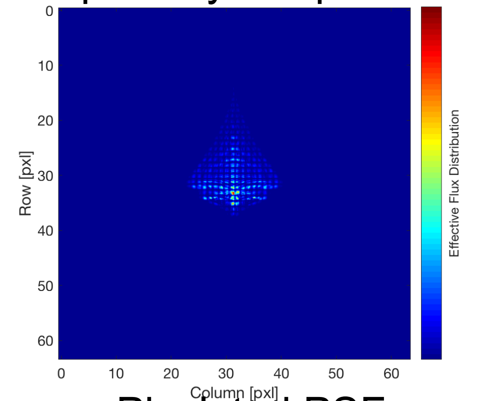


Translate, Pixelate, and Scale PSF

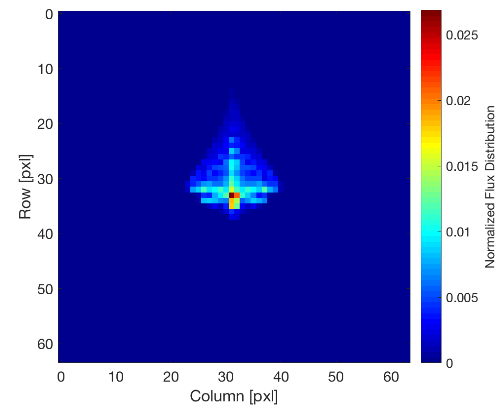
Subpixel Sensitivity Map



PSF Multiplied by Subpixel Sensitivity



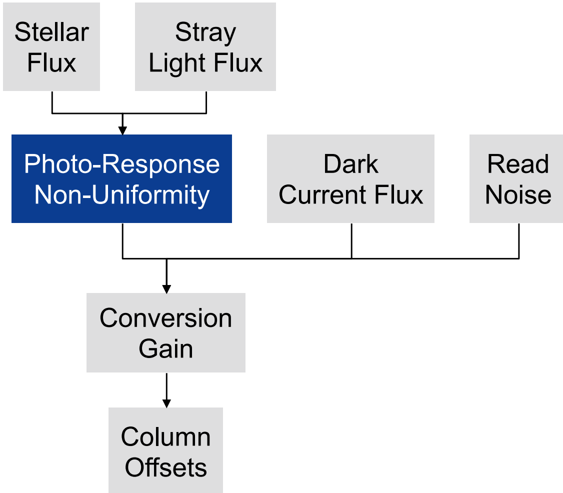
Pixelated PSF



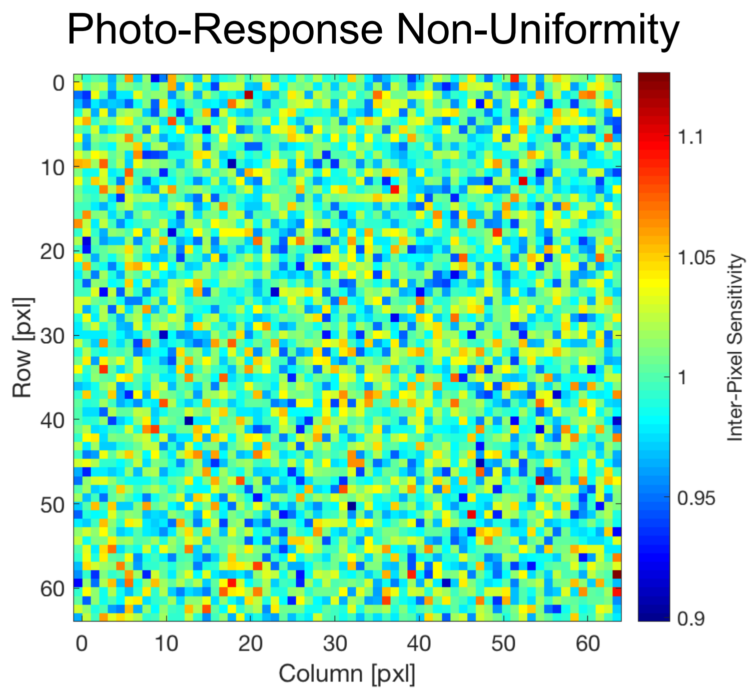
Stellar flux

$$S_P = \Phi_S \cdot \frac{\pi D^2}{4} \cdot \tau \cdot \Delta\lambda \cdot QE \cdot I(\theta) \cdot t$$

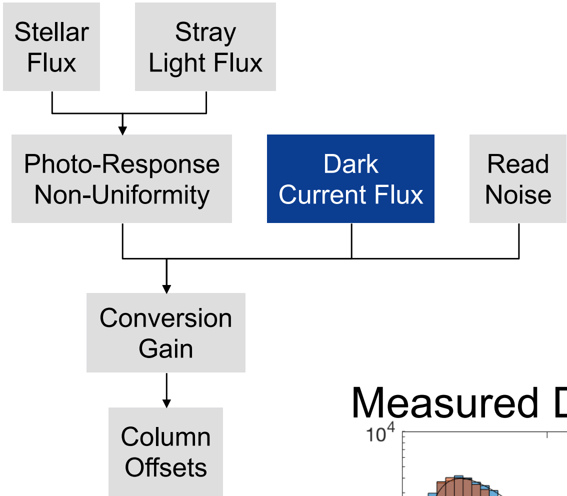
- Translate PSF onto centroid location in window via linear interpolation
- Multiply PSF with subpixel sensitivity (parameterized, but not based on measurements)
- Scale PSF by stellar flux



Randomize PSF

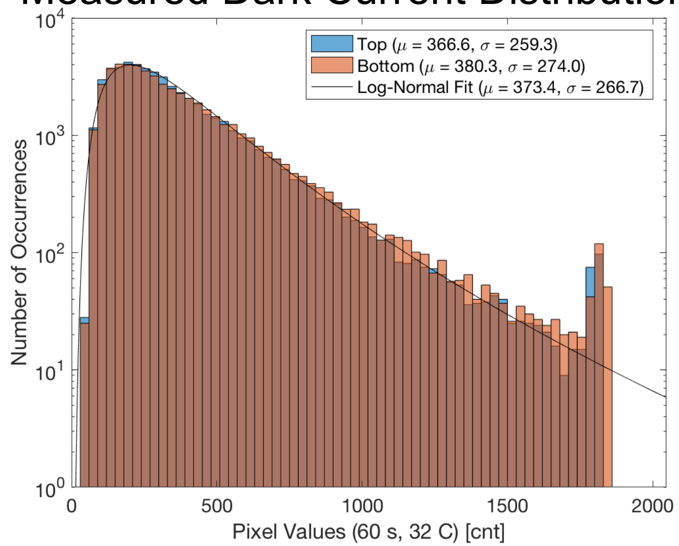


- Multiply PSF by photo-response non-uniformity (PRNU) (based on datasheet values)
- Draw signal electrons from Poisson distribution

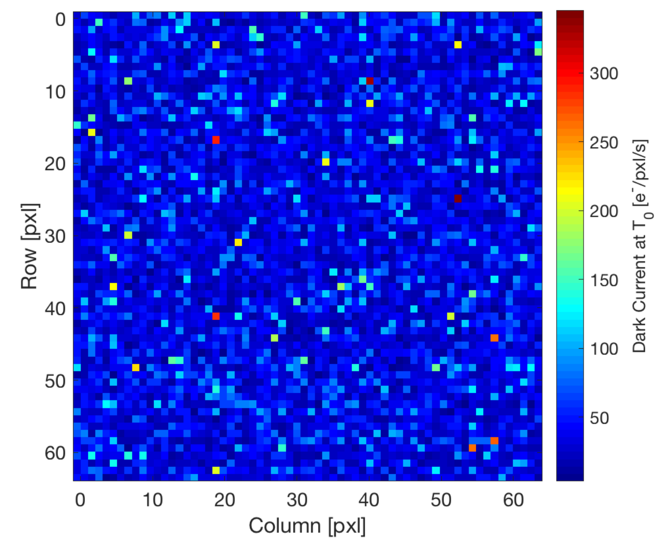


Compute Dark Current

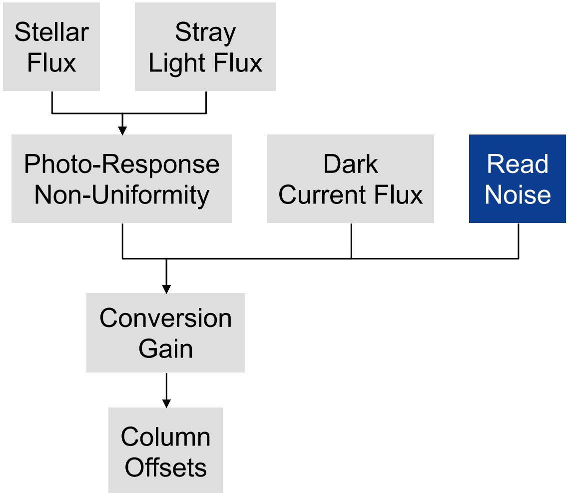
Measured Dark Current Distribution



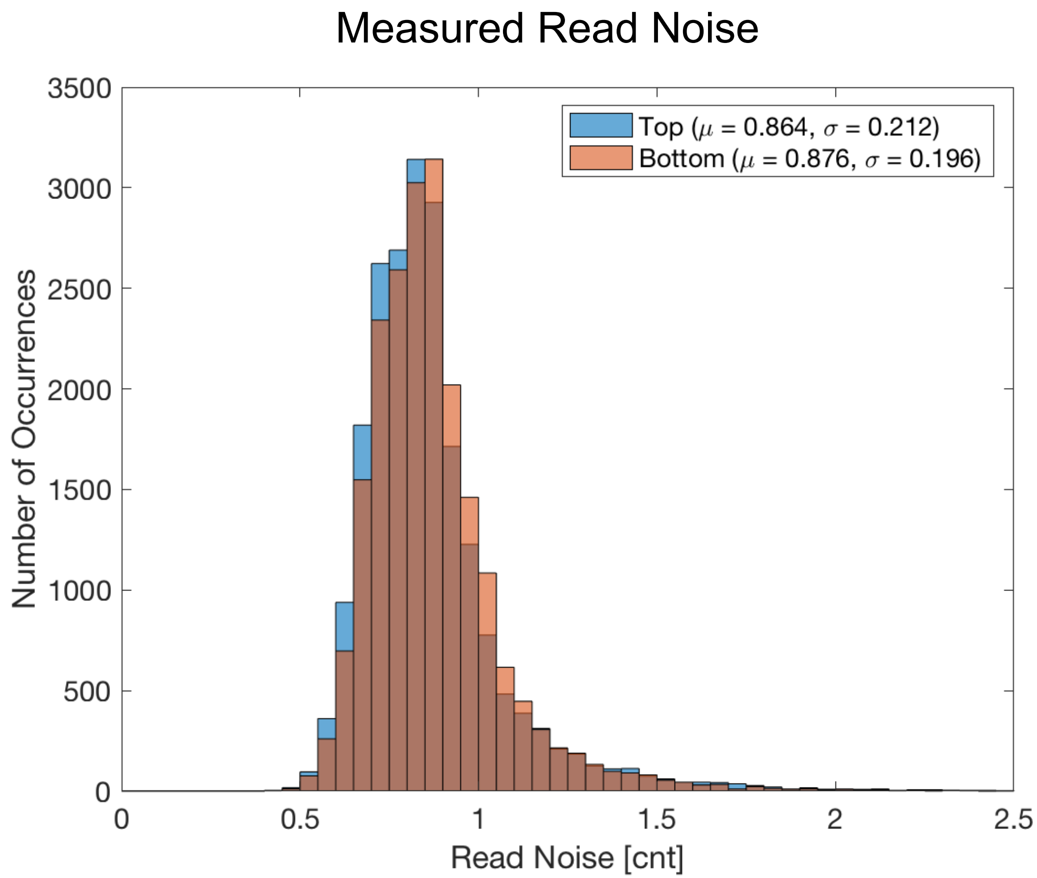
Simulated Dark Current



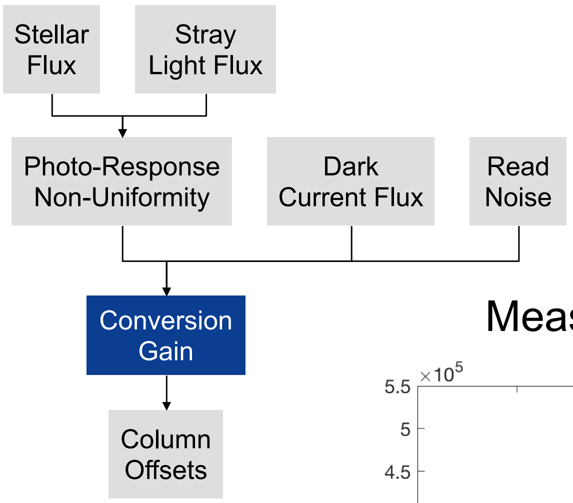
- Draw average dark current of each pixel from a log-normal distribution
  - Fit log-normal distribution to histogram of dark current measurements
  - Referred to as dark-current non-uniformity (DCNU)
- Draw dark current electrons from Poisson distribution



Add Read Noise

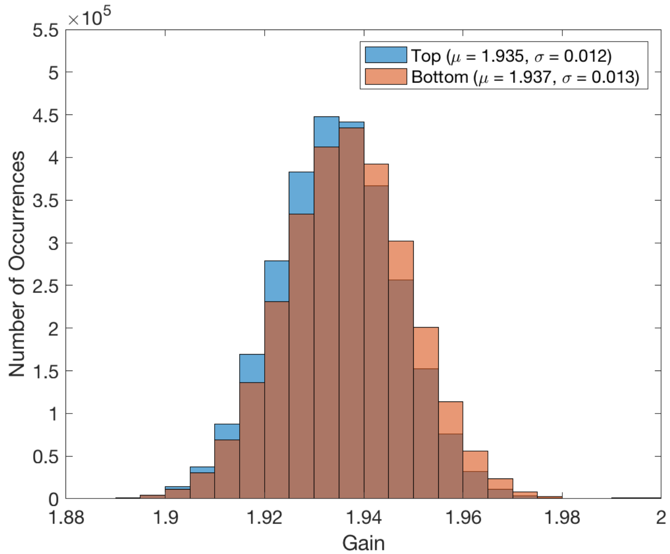


- Draw read noise electrons from a Normal distribution (measured values)

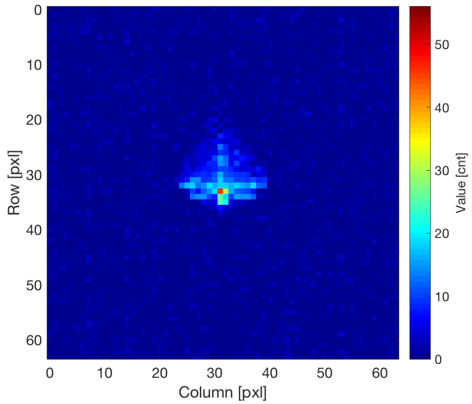


Convert Electrons to Counts

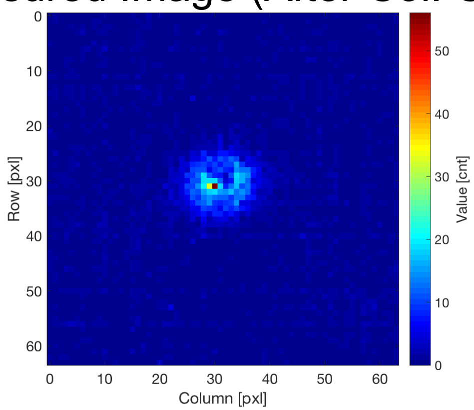
Measured Analog Gain



Simulated Image



Measured Image (After Col. Corr.)

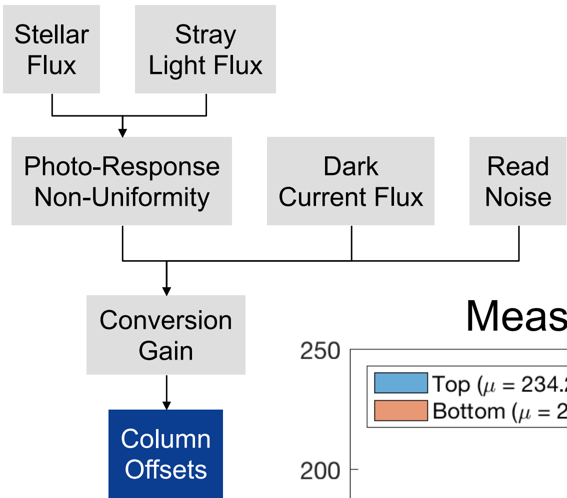


Conversion from Electrons to Counts

$$S_{\mathrm{cnt}} = \frac{2^{n_b} - 1}{\Delta v} \cdot g_{\mathrm{PGA}} \cdot g_{V/\mathrm{e}^-} \cdot S_{\mathrm{e}^-}$$

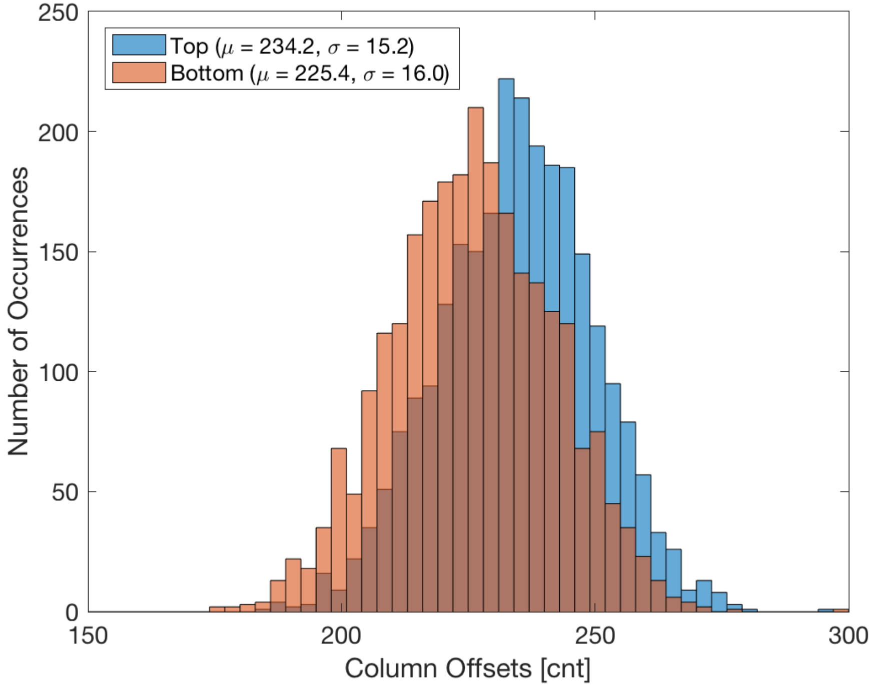
- Convert electrons to counts (measured analog gain, other values from datasheet)

Sim. and meas. images match well qualitatively in terms of signal and noise levels

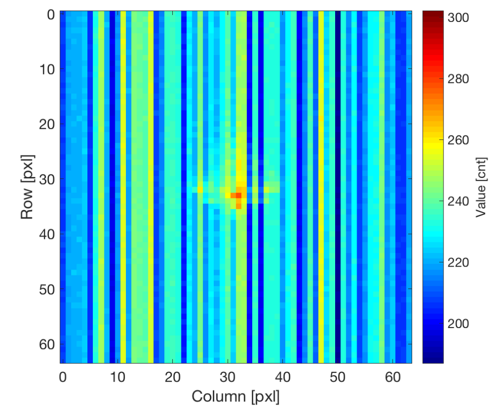


Add Column Offsets

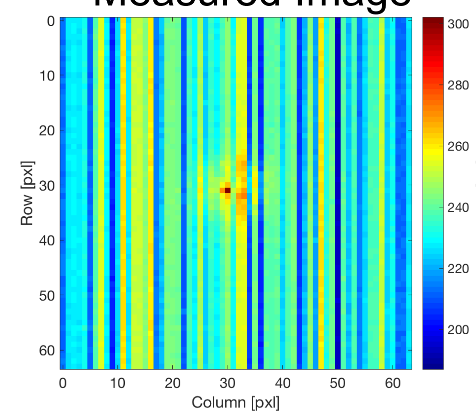
Measured Column Offsets



Simulated Image



Measured Image

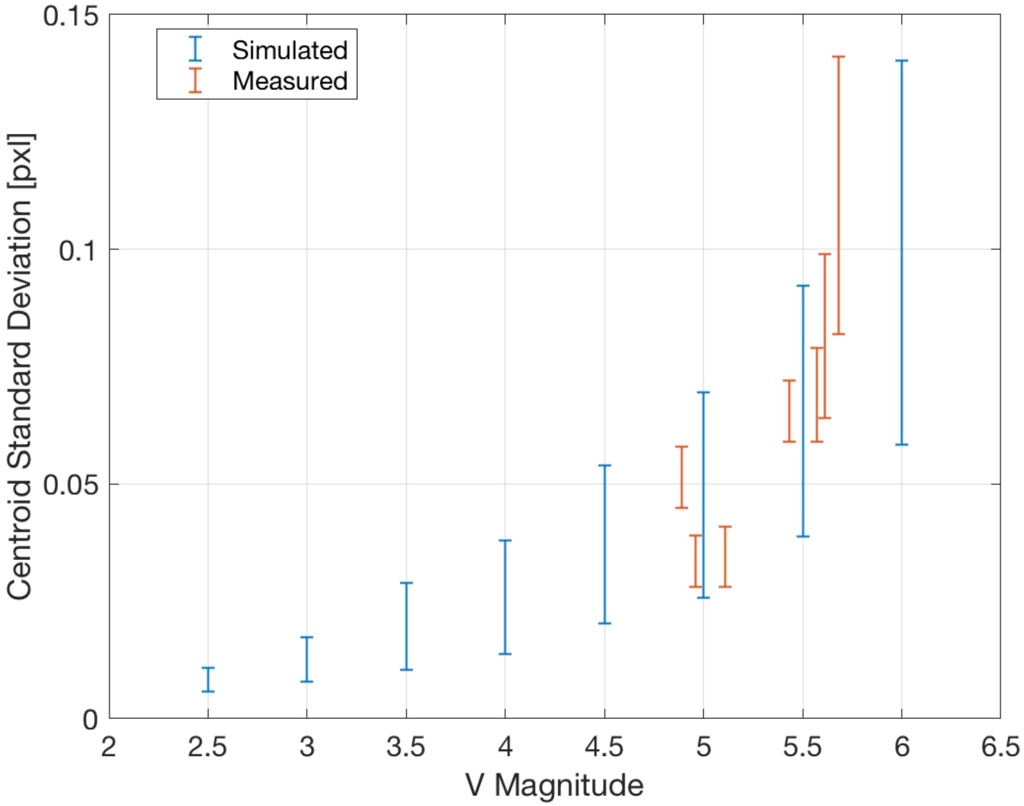


- Add column offsets (measured)
- Saturate and truncate counts

Raw images contain significant amounts of column offsets, which must be removed before centroiding

Centroid Standard Deviation vs. V Magnitude

- Used imager model to predict centroid standard deviation as a function of V magnitude
- Compared this against on-orbit telemetry



On-orbit measurements match predicted performance, validating imager model

Conclusions

- Provided an overview of the modeling and performance of the payload on ASTERIA, an important piece of the overall pointing performance puzzle
- A geometric camera calibration was presented and performed, showing centroid residuals less than 0.5 pixels RMS
- A model of star-tracker-to-payload alignment changes over time was created
- An imager model was presented and was able to correctly predict centroid errors in the range of 0.03 to 0.14 pixels RMS for stars with a V magnitude around 5 to 6, providing a validation of the imager model

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